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Climatological characteristics of sea breeze parameters at Chennai

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सार - इस शोध-पत्र में 1969 से 1983 तक के वर्षों के मार्च से अक्तूबर तक की अवधि के बृहत आंकड़ा आधार पर आधारित अनेक समुद्री समीर प्राचलों जैसे मानसून के आने, उसकी वापसी, उसके जारी रहने की अवधि, वर्षा की मात्रा और सघनता सहित दिशा की भिन्नता आदि के परिणाम प्राप्त किए गए हैं तथा चैन्नई शहर और चैन्नई ए.पी. स्थित वेधशालाओं के लिए इस शोध-पत्र में उनका अध्ययन किया गया है। इसमें अनेक समुद्री समीर प्राचलों की मासिक तथा उप-मासिक उपयोगिताओं के परिणामों का पता लगाया गया है। इसमें अध्यारोपित काल विश्लेषण की संकल्पना की सहायता से धरातल के तापमान तथा सापेक्षिक आर्द्रता की दैनिक भिन्नताओं का माडलन करने में समुद्री समीर की भूमिका के महत्व को बताया गया है1 चैन्नई की समुद्री समीर 1 कि.मी. के परिमाण तक हल्की पाई गई है। समुद्री समीर की मॉडल दिशाओं तथा इनकी सामान्य गति का पता भी इस शोध-पत्र में लगाया गया है।

ABSTRACT. Several sea breeze parameters such as time of onset, withdrawal, duration, depth, variation with height, direction *etc.* have been derived and studied for Chennai city and Chennai AP observatories in this study, which has been based on a large data base for the period March-October,1969-83. The monthly and sub monthly values of several sea breeze parameters have been derived. By invoking the concept of superposed epoch analysis the important role played by sea breeze in modulating diurnal variation of surface temperature and relative humidity has been established. The sea breeze at Chennai has been shown to be shallow with a depth of under 1 km. Modal directions of sea breeze and its normal speed have been derived.

Key words – Chennai, Chennai AP, Sea breeze, Onset, Withdrawal, Duration, Depth, Coriolis force, Superposed epoch analysis, Anti sea breeze, Mixing depth.

1. Introduction

Chennai located at 80.2° E, 13.0° N on the south east coast of India is an important metropolitan city of India, which till a few years ago was known as Madras in English. The city experiences year round warm to hot weather. Being a coastal station sea breeze is an important day to day mesoscale weather event experienced in Chennai during 7-8 months of the year covering the summer months and bringing considerable relief and respite to the residents of the city from the sweltering heat. Specific aspects of sea breeze at Chennai have been studied by Roy (1946), Rao (1955), Ramakrishnan & Jambunathan (1958). In this note we present the results of a study undertaken to derive several climatological features of sea breeze over Chennai. For complete details of the study and results reference could be made to Raj *et al*. (1998 & 2000).

2. Climatology of Chennai with reference to sea breeze

Chennai has two class I meteorological observatories Nungambakkam and Meenambakkam. The former representing Chennai city is located nearly 4 km west of the coast. The latter located southwest of the former away from the coast by nearly 10 km close to the airport is generally taken to represent the suburbs of Chennai and is also known as Chennai AP observatory. Fig.1 depicts the geographical location of Nungambakkam and Meenambakkam observatories.

It is well known from theory that sea breeze results from the development of solenoidal circulation generated from higher land surface temperature (LST) than sea surface temperature (SST) (Holton,1979). Surface friction and Coriolis force are other parameters influencing sea

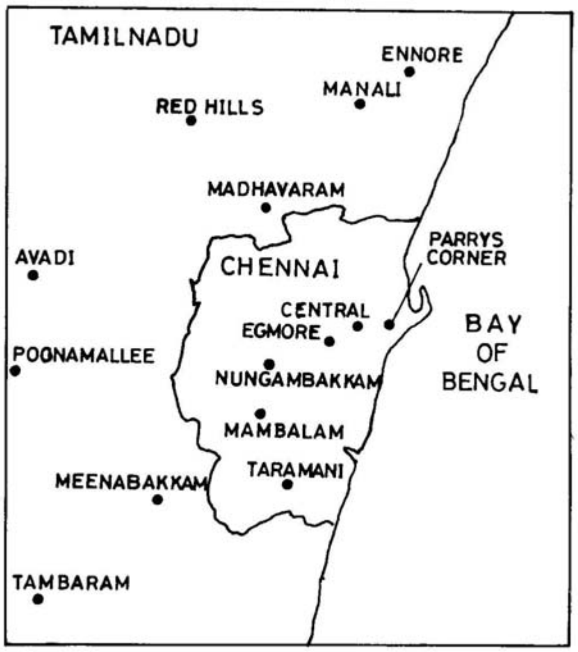

Fig. 1. Geographical location of Chennai and the Nungambakkam (city) and Meenambakkam (AP) observatories

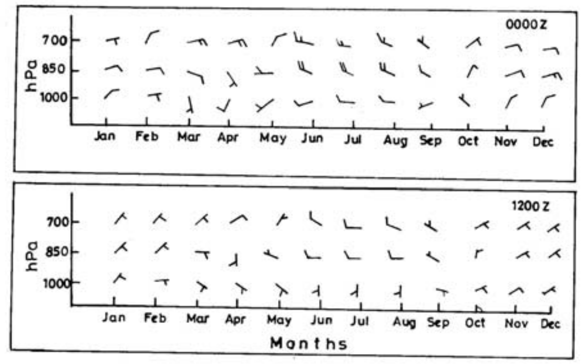

Fig. 2. Normal monthly low level wind over Chennai at 0000 UTC and 1200 UTC

breeze, but prevalent low level wind representing the larger flow pattern is perhaps the most important parameter influencing sea breeze parameters such as onset, duration, speed, spread, depth, intensity *etc*. As such we now present a brief discussion of the climatology of LST, SST and low-level winds over Chennai.

The monthly normal low-level wind pattern over Chennai at 0530 and 1730 hrs IST (0000 & 1200 UTC) during the year as obtained from India Meteorological Department (1988) is presented in Fig.2. Fig.3 depicts the normal monthly maximum temperature of Chennai and Chennai AP and the SST of Bay of Bengal (India Meteorological Department, 1999&1999). The SST generally varies between 27 and 30°C. During the months of November, December, January and February, the LST is unlikely to exceed SST substantially. Further, with the prevalent wind (as represented by the morning wind) being easterlies (Fig.2) a sea breeze front would not develop even with the development of solenoidal circulation. Thus it is obvious that sea breeze front would be clearly discernable during March-October only.

From the 0530 hrs upper air wind pattern, which by and large represents the larger flow (Fig.2) we observe that Chennai has two major low level wind regimes namely the westerly regime during April-October and the easterly regime during the remainder of the year. The low-level wind reverses from easterly to westerly roughly around 10 April and again reverses into easterly around 14 October. A comparison of the 0030 and 1730 hrs evening wind data of the period May-September clearly brings out the effect of sea breeze. Whereas the morning lower level winds are westerlies, the evening winds are south to south easterlies owing to the sea breeze effect. Though the reversal of normal wind from easterlies to westerlies takes place in April, preliminary examination of daily wind data for individual years revealed that the morning wind over Chennai even in March were westerlies on a good number of days.

In March and April on days when the low-level winds are easterlies, the development of solenoidal circulation due to LST exceeding SST, will result in building up of strong easterlies during forenoon and afternoon. This may result in a slight shift in the wind direction but not in a well defined sea breeze front. However once the low level morning winds are westerlies a sea breeze front gets established at the time of sea breeze onset (SBO) leading to noticeable fall of temperature and rise in humidity.

3. Objective of the study and data

In this study, for Chennai city and AP, we propose to

(*i*) Determine the time of SBO and sea breeze withdrawal (SBW) for a large number of individual days and hence derive climatology of SBO, SBW and duration of sea breeze.

(*ii*) Study the variation of surface temperature and relative humidity in association with SBO.

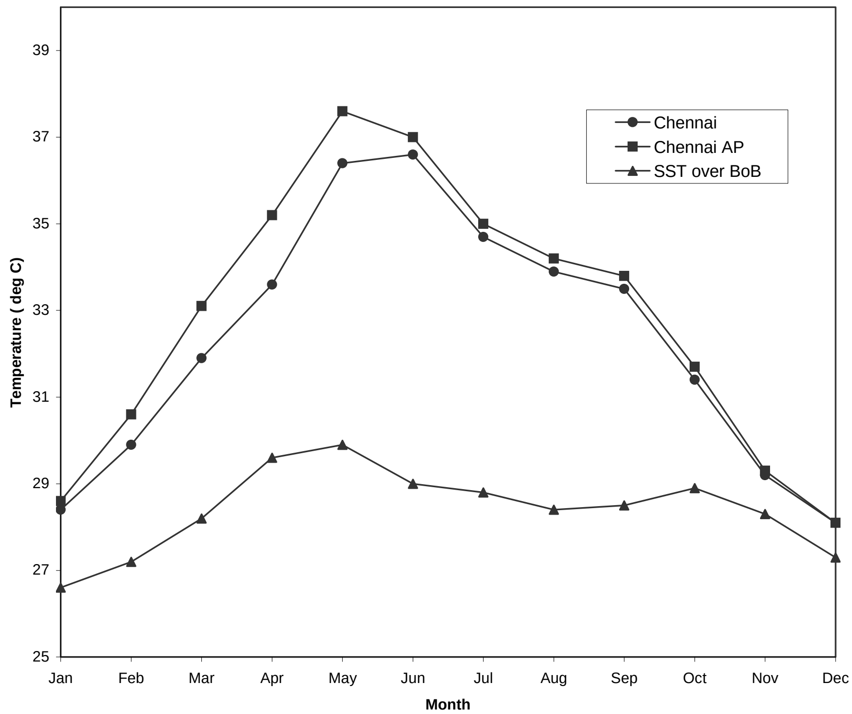

Fig.3. Normal daily maximum temperature at Chennai and Chennai AP and mean SST over Bay of Bengal

(*iii*) Derive the depth of sea breeze and its vertical profile.

(*iv*) Analyse direction of sea breeze.

The period of study has been taken as 1969-83, 1 March - 31 October. During the remainder of this period *viz*., November - February the low-level winds are easterlies with LST not substantially greater than SST and as such sea breeze is not clearly discernable.

3.1. *Data*

The digital, computerised autographic data of Chennai and Chennai AP for the period 1 March - 31 October for each year for the 15-year period 1969-83 were obtained from the National Data Centre, India Meteorological Department, Pune. This data set lists temperature (TT), relative humidity (RH) for every hour from 0100 to 2400 hrs. The mean and extreme values of TT and RH are also provided. Upper wind data at Chennai at 0530,1130,1730, 2330 hrs (IST) and the daily rainfall data for the period of study were also obtained and used in the study.

The autographic charts of Chennai and Chennai AP available at the Regional Meteorological Centre, Chennai

TABLE 1

Data used in the study, 1 March-31 October,1969-83 for Chennai and Chennai AP

Type of data	Parameters
For Chennai and Chennai AP	
Digital computerised autographic data for every hour	Temperature, Relative humidity
Daily rainfall data	Rainfall
For Chennai AP only	
Rawin data 0530 & 1730 hrs	Wind, height etc.
Pibal data 1130 & 2330 hrs (computerised)	Wind
Autographic charts (Continuous profile)	
Anemogram	Wind speed and direction
Thermogram/hygrogram	Temperature / Relative humidity

viz. Dines PT anemogram (for Chennai AP only), thermogram and hygrogram were also made use of. For Chennai AP anemograms for all the 15 years and hygrograms/thermograms for most of the years were referred. For Chennai atleast either hygrogram or thermogram for each year was referred.

Table 1 presents in a nutshell, details of data used in the study.

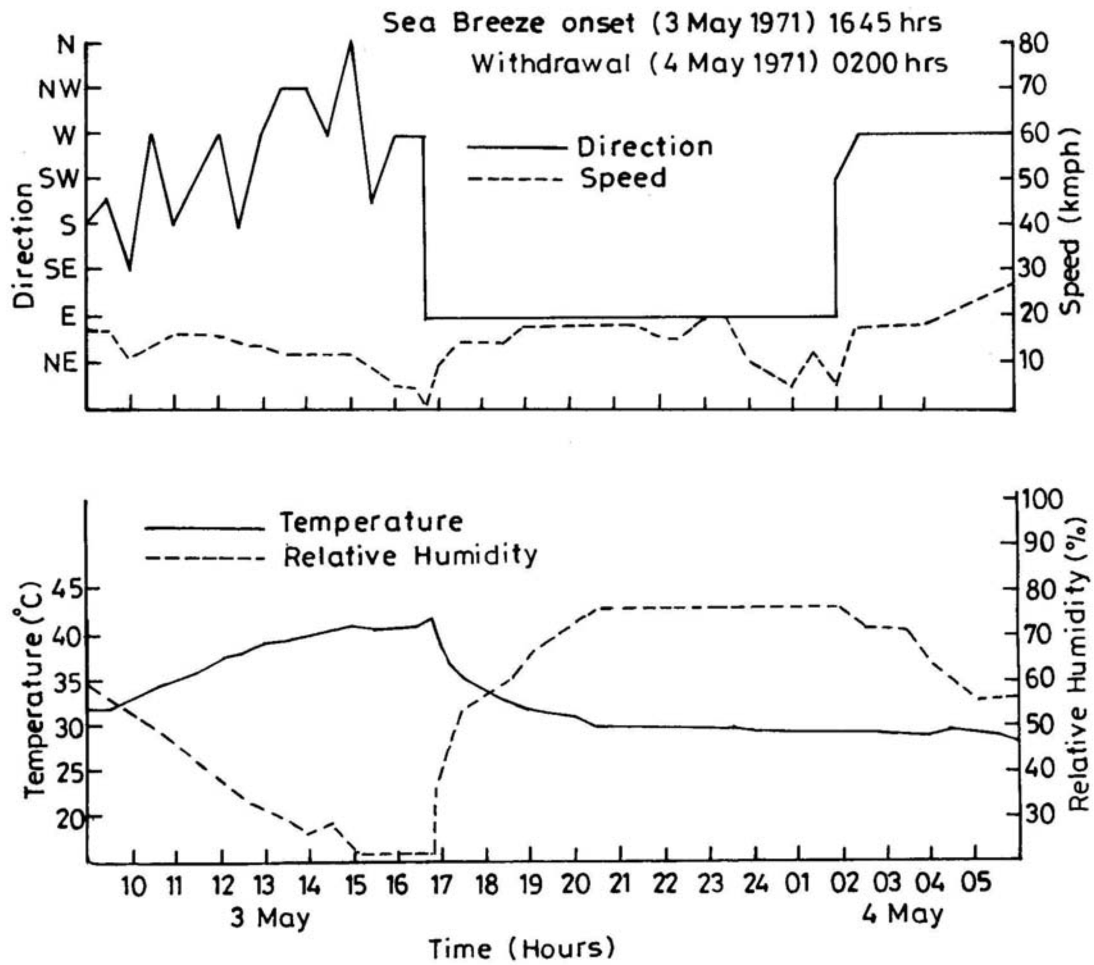

Fig. 4. Illustration of onset and withdrawal of sea breeze at Chennai Airport on 3 May 1971

4. Methodology for determination of SBO and SBW

4.1. *An illustration of SBO and SBW*

Fig.4 presents a classic instance of SBO and SBW wherein the anemogram, hygrogram and thermogram for Chennai AP for 3 May 1971 are depicted. As clearly observed, sea breeze sets in at 1645 hrs with wind direction suddenly reversing from W/SW 6-10 kmph to SE of 20 kmph accompanied by abrupt temperature decrease from 42-35 ° C in 1 hour and humidity rising from 35 to 52% in 15 minutes. However the withdrawal which takes place at about 0200 hrs (of 4 May 1971) occurs in a gradual fashion and could be determined only from the anemogram when the surface wind changes from SE/S to SW. Temperature and humidity do not show any discernable change concomitant with the time of SBW.

4.2. *Determination of time of SBO (For Chennai Nungambakkam and Meenambakkam)*

First, we determined the morning low level wind direction over Chennai as represented by the larger flow pattern. Determination of SBO was attempted only when this direction was westerly. Now, in March and April during late night the LST could be considerably lower than the SST resulting in development of westerly land breeze (Raj and Nageshwari, 2000) which normally would decay in the morning itself. By referring to the anemogram and the morning low level winds the wind direction representing the over all flow could be correctly determined, despite the influence of land breeze. In October low level winds reverse to easterlies around 14 October followed by onset of northeast monsoon rains. SBO was not determined for this period also.

TABLE 2

Normal time(IST) of sea breeze onset (smoothed) for 10/11 day periods (Apr-Sep)

Period	Chennai	Chennai AP
01-10 Apr	1120	1225
11-20 Apr	1125	1230
21-30 Apr	1135	1240
01-10 May	1200	1300
11-20 May	1230	1335
21-31 May	1305	1410
01-10 Jun	1345	1450
11-20 Jun	1425	1525
21-30 Jun	1455	1550
01-10 Jul	1510	1555
11-20 Jul	1515	1555
21-31 Jul	1515	1600
01-10 Aug	1525	1605
11-20 Aug	1525	1610
21-31 Aug	1510	1555
01-10 Sep	1445	1530
11-20 Sep	1415	1500
21-30 Sep	1355	1440

If the morning wind was westerly the anemogram was studied to fix the time of SBO, which could be easily defined as the time when the wind changes from westerly to easterly. Generally this change over was abrupt and sudden and so the onset time could be fixed without much ambiguity. The profile of RH showed a sharp rise at the time of SBO whereas that of TT manifested a decrease, some times sharp and some times gradual. If the SBO occurred before noon, TT did not always decrease but remained stationary for some time, subsequently. For Chennai AP the onset time was determined from the anemogram and was corroborated with the time of RH cut off and the decrease/stationarity of TT. Mostly the above features coincided and difference when sometimes observed, was negligibly small.

For Chennai (Nungambakkam) the determination has to be based only on the thermogram and/or hygrogram. The RH cut off at the time of SBO was found to be less sharp at Chennai when compared to Chennai AP especially in March and April. During the months of June, July, August and September that constitute the southwest monsoon season, Chennai has 4-8 rainy days for each month. This shows that there is a fair chance of a day being rainy under favourable synoptic situations. The

TABLE 3

Normal time of sea breeze onset , withdrawal and duration at Chennai and Chennai AP

Month	O1	O2	W2	OL	D2	N1	N2
Mar	1130	1230	0230	60	1400	124	168
Apr	1125	1230	0245	65	1415	213	258
May	1230	1335	0150	65	1215	327	354
Jun	1420	1530	0020	70	0850	306	315
Jul	1515	1555	0000	85	0810	314	325
Aug	1525	1610	0015	95	0805	297	317
Sep	1420	1505	0035	45	0930	280	310
Oct	1325	1405	0125	40	1115	77	98

Based on 1969-83 data (Time local, IST)
O1,O2 - Onset at Chennai, Chennai AP
W2,D2 - Withdrawal, duration at Chennai AP
N1,N2 - Sample sizes for Chennai and Chennai AP (No. of days monthwise)
OL - Lag of onset between Chennai and Chennai AP

occurrence of rain at times could manifest the same signals that are associated with SBO such as RH cut off to higher values, decrease of TT *etc*. For all the days of the study the daily rainfall data set of Chennai and Chennai AP were referred and for a rainy day the autographic charts/data analysed much more critically. In case the occurrence of rainfall was found to have vitiated the SBO, no determination of onset was attempted for that day.

The determination of time of SBO for both Chennai and Chennai AP was thus carried out for the period 1 March - 31 October, for 1969-83 in accordance with the methodology described above. The onset time was fixed with an accuracy of 15 minutes, *i.e*. onset time determined as 1100, 1115, 1130, 1145, 1200 hrs *etc* (IST). The time of SBO could not be determined for several days. Non determination on a particular day was due to either or combination of the following factors: (*i*) Prevalent low level wind was easterly in the morning. (*ii*) Low LST than SST and so no sea breeze development. (*iii*) Sea breeze may have developed but onset time could not be firmly determined from the data profiles. (*iv*) Strong westerly winds retarding sea breeze. (*v*) Rain during the day vitiating SBO. (*vi*) Ambiguity in determination and (*vii*) Inconsistencies in the data or missing data. For Chennai, SBO could be determined for 1939 days or 56.8% of the total no of 3675 days. For Chennai AP the figures are 2145 days or 58.4%. For a year on an average onset could be determined for 129 days for Chennai and 143 days for Chennai AP during March-October. As for

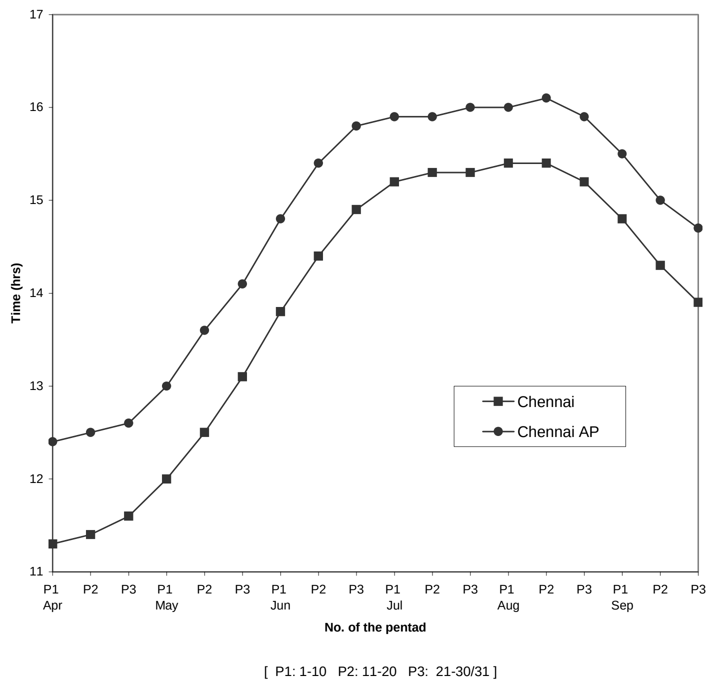

Fig.5. Normal time (IST) of sea breeze onset at Chennai & Chennai AP

normal monthly variation, onset could be determined only for 8 and 11 days in March and 5 and 7 days in October respectively for Chennai and Chennai AP. The maximum number of determination was 22 and 24 days respectively in May for Chennai and Chennai AP.

4.3. *SBW (For Chennai Meenambakkam only)*

The time of occurrence of SBW was determined for a given day only if SBO had already taken place on that day, as elucidated in the previous section. The profile of wind direction was critically studied and the time of reversal of surface wind from easterly to westerly was determined. Unlike SBO, the change in the wind direction was gradual in respect of SBW making the determination only approximate (Fig. 4). Determination of time of SBW was done with an accuracy of 15 minutes. Non determination for a day was generally due to (*i*) No SBO and so no SBW (*ii*) withdrawal not at all clearly defined (*iii*) Rain/thunderstorm vitiating wind data (*iv*) Missing/ unreliable data. The dates of SBW were determined for 1 March - 31 October, 1969-83. In all, time of SBW could be determined for 1985 days out of 2145 days for which SBO was determined *i.e.*, SBW could be determined for 93.5% of the day for which SBO was determined.

5. Results and discussion

The data on time of SBO and SBW generated were subjected to various types of analysis to bring out the features associated with them. These results and those obtained from various other analysis are discussed below.

5.1. *Normal time of SBO*

The mean time of onset for 10/11 day periods *viz*., 1-10, 11-20, 21-30/31 *etc*. for the 8 months was computed by pooling the onset times over the above periods and the 15 year period. A weighted moving average filter smoothed the 24 means thus obtained and the smoothed values were taken as the normal values. Table 2 presents the normal SBO time over Chennai and Chennai AP during the eighteen 10/11 day periods covering April to September. The data for March and October are not included in the Table as the means were based on small samples though these were used for smoothing. Fig.5 presents the intra-annual variation of the normal time of SBO graphically. Tables 3 and 4 present the normal data for all the months (unsmoothed) along with the standard deviation and range. The monthly variation of time of

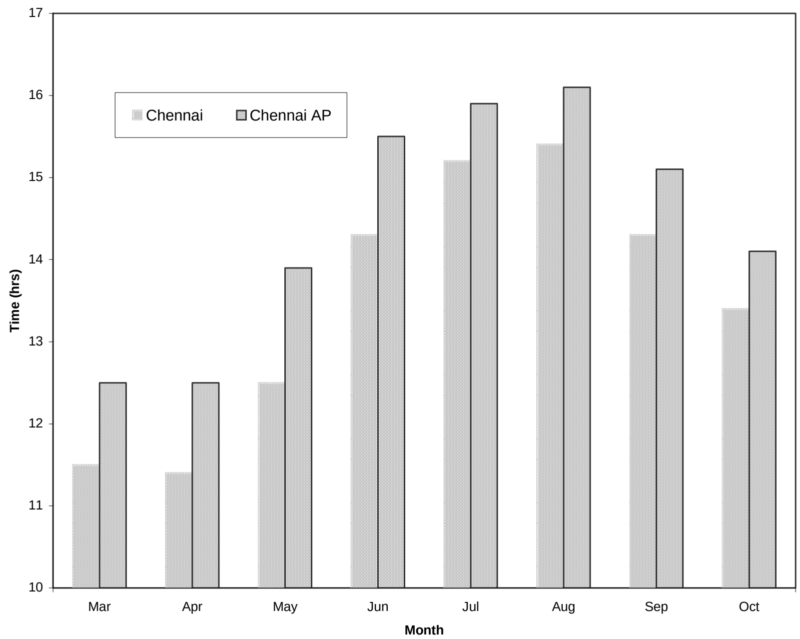

Fig.6. Normal time (IST) of sea breeze onset, monthwise at Chennai & Chennai AP

SBO is depicted in Fig.6. From Tables 2-4, Figs. 5&6 and the set of onset dates the following features could be inferred.

For Chennai the normal time of onset is around 1130 hrs in March and April which progressively gets delayed to 1230 hrs in May, 1420 hrs in June, nearly 1530 hrs in July and August. It then becomes early at 1420 hrs in September and 1325 hrs in October. The standard deviation is 100-115 minutes during June - September but is lower during the other months.

At Chennai AP the SBO takes place 40-65 minutes after the onset at Chennai, the maximum difference obtained during May and June (Table 5). The normal onset which is at 1230 hrs during March and April gets delayed to 1330 hrs in May, 1530-1600 hrs in June and July, then to as late as 1610 hrs during August. The time of SBO then advances to nearly 1500 hrs in September and 1400 hrs in October. The time of SBO during the 8 month period shows a very large variation with a range of 0930-2145 hrs for Chennai and 1015-2215 hrs for Chennai AP. On 8.5% of the days onset over Chennai and Chennai AP coincided whereas on 3.6% on the days onset first took place at Chennai AP and then at Chennai despite the latter's location closer to the coast.

5.2. *Intra-seasonal variation of time of SBO vis-a-vis maximum temperature and prevalent surface wind*

We observe from Fig.3 that the maximum temperature of Chennai increases from March to May and so evidently increasing amount of LST and SST contrast is realised in May compared to March / April. As the acceleration of wind generated by the solenoidal circulation (without taking friction into consideration) is directly proportional to the LST-SST contrast it is evident that higher wind speed would be generated from the solenoidal circulation in May compared to the preceding months (even after friction is taken into consideration). However the sea breeze as observed is the resultant wind of the solenoidal wind and the surface wind representing the larger flow pattern. The monthly normal 1000 hPa 0530 hrs (IST) zonal wind at Chennai for March-October is presented in Table 5. The zonal wind increases sharply from March to June and then gradually decreases. Thus convergence generated from sea breeze circulation increases in May and June compared to the preceding months resulting in vertical transfer of horizontal momentum and delay in sea breeze onset.

TABLE 4

Variability of normal time of sea breeze onset, withdrawal and duration for Chennai and Chennai AP, March - October

Month	Standard deviation				Range	
	O1	O2	W2	D2	O1	O2
Mar	40	55	110	115	1000-1330	1045-1515
Apr	60	65	140	140	0930-1515	1015-1545
May	85	90	195	225	0930-1915	1045-2115
Jun	100	105	160	205	1000-2100	1115-2215
Jul	105	105	150	175	1115-2045	1130-2115
Aug	110	105	140	175	1130-2145	1215-2145
Sep	115	110	155	195	1015-2130	1030-2215
Oct	95	105	180	230	1015-1815	1130-1930

Foot notes as in Table 3

TABLE 5

Normal 0530 hrs 1000 hPa zonal wind and maximum mixing depth at Chennai

Month	U	H
Mar	-0.3	430
Apr	0.6	690
May	2.7	710
Jun	5.8	795
Jul	4.9	800
Aug	4.9	660
Sep	3.8	770
Oct	2.3	510

U - Zonal wind (m/s)
H - Mixing depth (metres)

To get further insight into this aspect we have computed the maximum mixing depth at Chennai based on 0530 hrs IST (0000 UTC) normal data (India Meteorological Department, 1988) by following Holzworth method (Holzworth, 1967). The assumption here is that in a thoroughly mixed unsaturated atmosphere the temperature lapse rate is dry adiabatic. For an urban environment an overall average value of 4º C may be added to the surface temperature (Jayanthi,1988). The normal mixing depths of Chennai have been derived and are presented in Table 5. The mixing height increases from March to June from nearly 430 m to 800 m facilitating increased vertical transfer of momentum in May compared to preceding months. In subsequent months the maximum temperature decreases but zonal wind strengthens leading to further delay of sea breeze onset, which is accompanied by fairly high values of mixing depth in June and July.

The monthly variation of time of onset of sea breeze can be convincingly explained by resorting to multiple correlation analysis. If w is the time of sea breeze onset (in hours), x is the maximum temperature (in °C) and u is the 1000 hPa 0530 hrs IST zonal wind (m/s) the regression equations for Chennai and Chennai AP based on monthly data are derived as:

$$W = -0.36x + 0.85u + 23.2$$

$$W = -0.20x + 0.71u + 19.3$$

respectively. The multiple correlation coefficients obtained are 0.98 and 0.98 explaining 95.4 and 96.5% respectively of the total variation. The negative sign associated with x clearly shows that given u sea breeze sets in early when x is high and late when x is low at the rate of 0.36 hr or 22 min per deg C in Chennai and 12 min at Chennai AP. Similarly given x , onset gets delayed with increasing u at the rate of 51 & 43 min per every m/s respectively at the two locations. From the above analysis it is evident that SBO at Chennai city closer to the sea, is more sensitive to changes in temperature and surface wind compared to that at Chennai AP.

5.3. *Superposed epoch analysis*

The superposed epoch analysis is capable of bringing out the sudden change of weather parameters with reference to any specific weather event (Panofsky and Brier, 1968). We have utilised this concept to clearly bring out the changes in temperature and relative humidity at the time of SBO. The profiles of TT and RH were obtained at -3, -2, -1, 0, 1, 2, 3 hrs with reference to the onset time with 0 hr representing the time of onset. The values of TT, and RH were linearly interpolated from the hourly profiles. However for 0, which denotes the exact onset time the lowest value of RH and highest value of TT (which is the maximum temperature) were assigned, as normally occurrence of RH minimum and TT maximum coincided with the time of onset. In a few cases when the above condition was not met, linear interpolation determined the values at 0. Such profiles were assimilated for all the, 8 months of study and averaged over the 15 years. These are presented in Table 6. The changes of the values of parameters from 0 to 1 hour, which are the most prominent are given in the last column of the same table.

TABLE 6

Variation of temperature and relative humidity with reference to sea breeze onset at Chennai and Chennai AP : Superposed epoch analysis

H: ->		-3	-2	-1	0	1	2	3	D01
I TT	Mar	27.4	29.3	31.0	32.6	32.0	31.8	31.5	-0.6
	Apr	29.7	31.3	32.7	34.3	33.3	33.1	32.9	-1.0
	May	33.2	34.7	36.0	37.3	34.9	34.2	33.5	-2.4
	Jun	34.0	35.1	35.9	36.7	33.5	32.5	31.8	-3.2
	Jul	32.8	33.6	34.2	34.8	31.9	31.0	30.4	-2.9
	Aug	32.2	33.0	33.4	33.9	31.4	30.5	29.8	-2.5
	Sep	31.3	32.2	32.9	33.6	31.6	30.9	30.4	-2.0
	Oct	30.5	31.6	32.4	33.2	31.9	31.4	31.0	-1.3
II TT	Mar	28.9	30.7	32.3	33.6	32.9	32.6	32.0	-0.7
	Apr	31.5	33.1	34.5	35.7	34.6	34.2	33.6	-1.1
	May	34.7	36.1	37.2	38.2	35.9	35.0	34.0	-2.3
	Jun	35.3	36.1	36.6	37.2	33.7	32.6	31.8	-3.5
	Jul	33.5	34.2	34.6	35.1	32.0	31.0	30.2	-3.1
	Aug	32.8	33.4	33.7	34.0	31.2	30.2	29.5	-2.8
	Sep	32.0	32.7	33.2	33.7	31.5	30.7	30.0	-2.2
	Oct	30.9	31.8	32.5	33.2	31.6	31.1	30.5	-1.6
I RH	Mar	76	66	57	50	57	58	59	7
	Apr	75	66	60	53	60	61	63	7
	May	57	51	47	42	54	57	61	12
	Jun	50	46	44	42	56	61	66	14
	Jul	54	52	51	49	63	68	72	14
	Aug	57	55	54	52	67	71	75	15
	Sep	64	60	59	56	67	71	73	11
	Oct	68	62	60	56	67	68	70	11
II RH	Mar	64	53	45	39	49	50	52	10
	Apr	60	51	44	39	50	52	55	11
	May	46	40	36	33	47	51	55	14
	Jun	40	37	36	34	54	59	64	20
	Jul	47	45	43	42	62	68	72	20
	Aug	49	47	46	45	67	73	77	22
	Sep	54	50	48	45	64	69	73	19
	Oct	60	54	51	48	62	65	68	14

H - Hour *w.r.t* sea breeze onset, TT- temperature in °C, RH - Relative humidity in % , D01- Change within 1 hour, from onset I - Chennai II - Chennai AP

From Table 6 the following inferences could be drawn. The hourly TT during the period March-October, invariably increases from -3 to 0 followed by a sudden drop from 0 to 1 then steady and gradual decrease for the hours 1 to 3. It is interesting to observe that this is the profile of TT even during the individual months of July

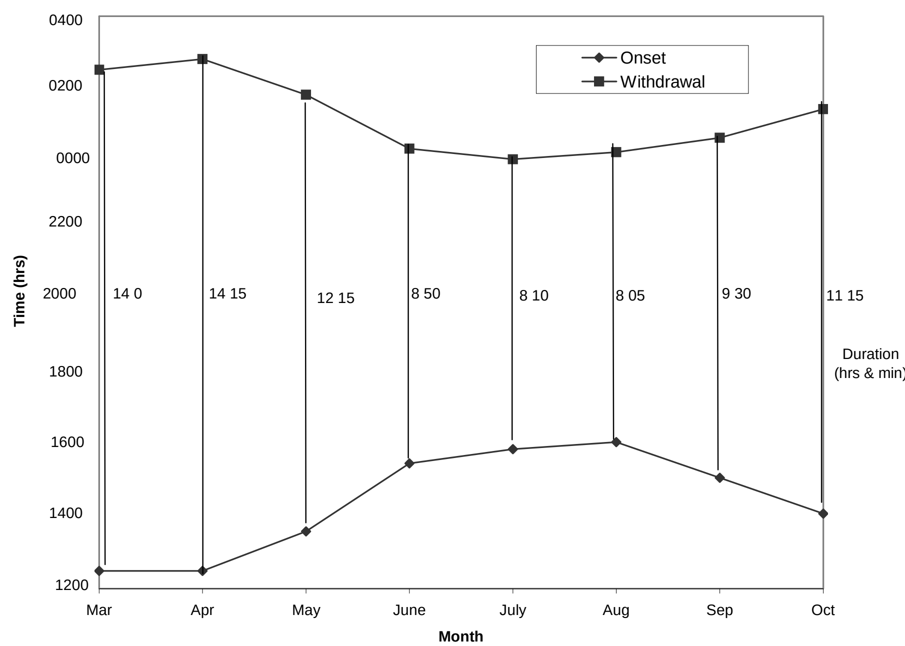

Fig.7. Monthly variation of normal time of onset, withdrawal and duration of sea breeze at Chennai AP

and August for which the normal time of SBW is during 1500-1615 hrs. It is well known that for Chennai, the maximum solar radiation is received at about 1200 hrs and the maximum temperature is expected to be realised at about 1400 hrs due to solar-terrestrial radiation balance. Despite these theoretical considerations the TT manifests a normal profile with maximum temperature being realised closer to the time of SBO.

This shows that sea breeze modulates the diurnal variation of temperature substantially. The RH profiles show decrease from -3 to 0 and then increase from 0 to 3.

The last column of Table 6 presents the TT/RH change from the time of onset to 1 hr after the onset. For TT the decrease varies from 0.9 to 3.2° C at Chennai and 0.9 to 3.6° C at Chennai AP. The maximum decrease is observed during June. For RH the increase varies from 6 - 16% at Chennai but 10 - 22% at Chennai AP. These figures show that SBO is much more conspicuous and easily discernable at the slightly interior Chennai AP than at Chennai city located closer to the coast.

5.4. *Normal time of SBW (for Chennai AP only)*

The normal time of SBW was computed for all the 8 months from March to October from the SBW dates generated. Tables 3 & 4 present the normal time of SBW and the standard deviation of the normal. It is seen from Table 3 that the normal occurrence of SBW which is nearly 0230 hrs during March and April advances to 0150 hrs during May, 0020 hrs in June, 0000 hrs in July. It then gets delayed to 0015 hrs in August, 0035 hrs in September and 0135 hrs in October. Thus the normal time of SBW displays a pattern which contrasts with that of time of SBW *i.e*., early withdrawal corresponding to late onset.

5.5. *Duration of sea breeze*

Table 3 presents the duration of sea breeze for each month derived from the data on onset and withdrawal. The duration which is nearly 14 hrs during March and April reduced to nearly 12 hrs during May, 9 hrs during June, 8 hrs in July and August, increases to 9½ hrs in September and to 11 hrs in October. Fig.7 depicts the variation of time of onset, withdrawal and duration of the sea breeze at Chennai AP.

5.6. *Depth of sea breeze*

The upper wind observations at Chennai AP are taken at 0530 and 1730 hours (Radiowind data) and at 1130 and 2330 hrs (Pilot balloon data). The Rawin data

TABLE 7

Normal sea breeze height over Chennai AP

Month	Time (IST hrs)		
	1130	1730	2330
Mar	385	650	725
Apr	460	660	655
May	465	740	540
Jun	–	625	375
Jul	–	510	445
Aug	–	490	485
Sep		635	640
Oct	–	765	795

Height in metres, each normal based on 35-193 observations

are available at every 50 hPa level from 1000 hPa level whereas the pilot balloon data are available at Ground, 150, 300, 600, 900, 1500 metres a.s.l and above. The height of the sea breeze front was determined at 1130, 1730 and 2330 hrs for days with discernable SBO by resolving the winds at all the levels and then interpolating the height at which the zonal wind changed into westerlies. Hourly average of the heights were obtained for all the months. The normal depths of SB obtained from the above computation along with the number of days from which the means were computed are presented in Table 7.

It is seen that the sea breeze front over Chennai lies within 800 m (normally) for all the months and for all the hours. At 1130 hrs the height could be determined only for the 3 month period March - May, as during the remaining months of June-October sea breeze normally sets in after 1130 hrs only. At 1730 hrs the monthly range of height is 500-800 m and at 2330 hrs it is 400-800 m. Generally the sea breeze reaches the maximum height at 1730 hrs except for September and October when the heights at 1730 and 2330 hrs are almost equal.

It is evident from the magnitudes of heights obtained that the sea breeze front over Chennai does not extend to great heights, say to 1 - 2 km as quoted frequently in the literature and as obtained for Bombay by Mukherjee *et al*. (1985). A plausible ascription for this feature could be that the sea breeze front over Chennai gets established during pre-monsoon and monsoon seasons against fairly strong westerlies, which are capable of impeding its vertical spread.

5.7. *Variation of sea breeze with height*

The vertical profile of SB was also examined in detail for the various hours for different months. The level at which the SB reaches the maximum intensity (*i.e*., maximum easterly wind) was identified. Table 8 presents the two levels at which the maximum frequencies of SB maximum were reached for different hours and months along with the mean maximum winds.

TABLE 8

Modal levels at which sea breeze at Chennai is maximum and magnitude of the easterly wind

	1730 hours			2330 hours		
	Lvl (hPa)	*N* (%)	|*u*| (kmph)	ht asl (metres)	*N* (%)	|*u*| (kmph)
Mar	1000	49	15.6	150	24	16.6
	950	11	16.2	300	13	15.5
Apr	1000	66	16.6	150	27	13.7
	950	16	16.6	300	22	15.5
May	1000	48	14.0	150	53	0.7
	950	46	14.0	300	15	9.4
Jun	1000	53	13.0	150	76	0.4
	950	43	10.4	300	12	4.3
Jul	1000	61	11.9	150	67	1.1
	950	38	9.7	300	21	5.4
Aug	1000	75	10.8	GR	59	0.7
	950	22	11.1	150	23	5.0
Sep	1000	70	12.6	GR	36	0.7
	950	24	14.0	150	24	6.5
Oct	1000	62	13.3	150	25	8.3
	950	32	13.7	300	21	10.8

Lvl - Pressure level, *N* - Percentage frequency,
GR- Ground level, *u* - Zonal wind

Now, by and large the SB does not set in before 1130 hrs and is closer to the withdrawal phase at 2330 hrs. Therefore the observation at 1730 hrs could be taken as the best representative of the maximum sea breeze speed within the framework of available upper air data. As seen from Table 8 the maximum speed is obtained either at 1000 hPa or at 950 hPa for all the months and these two levels account for 82-100% of the maximum winds save for March. The mean speeds vary between 10 - 17 kmph.

At 2330 hrs the maximum speeds are obtained at 150 metres a.s.l during March and April. During May-June the sea breeze is closer to withdrawal at this time and so it extends only closer to the ground level on most of the occasions with almost zero easterly speed. However on

TABLE 9

Prominent sea breeze directions at Chennai AP

Month	Direction (Percentage frequencies)			Maximum wind (Speed kmph)		
	E	SE	S	E	SE	S
Mar	3	75	22	13	17	8
Apr	3	67	30	15	19	11
May	5	56	39	14	18	14
Jun	2	57	41	10	17	15
Jul	3	60	37	12	15	15
Aug	1	60	39	11	13	13
Sep	6	61	33	11	13	11
Oct	13	63	24	9	12	10

days when it extended to higher levels the maximum speeds were obtained at 150 metres a.s.l, with speeds in the range of 5-10 kmph.

The above exposition pertaining to sea breeze at Chennai confirm to and reinforce the general theory that sea breeze obtains its maximum strength just above the ground level and the strength decreases aloft.

5.8. *Spatial variation of SBO and SBW*

The normal time of onset of sea breeze showed substantial spatial variation as evidenced by the nearly 1 hr time lag of SBO at Chennai AP compared to the city (Nungambakkam), which itself is located nearly 4 km away from the coast (Table 3).Presuming that withdrawal also manifests a similar lag with the sea breeze front moving towards the coast during the withdrawal phase, the duration of sea breeze in the city is expected to be atleast 90 minutes, more than that over Chennai AP and still more at locations very close to the coast. These aspects have to be taken into consideration while interpreting the normals of sea breeze parameters derived in the study for different locations of the city.

5.9. *Direction of sea breeze*

During the course of a day the sea breeze may blow from two or three prominent directions from the sea. To study this aspect, the anemograms of all the days were examined in detail and the prominent directions (within 8 points of the compass) and the maximum sustained speeds corresponding to the directions were extracted. Table 9 presents the prominent wind directions, their frequencies and the corresponding mean wind speeds. It is seen that sea breeze from N or NE direction is completely absent for all the months. The prominent directions are southeasterly and southerly. Sea breeze blowing from easterly direction is also rare and is maximum at 13% during October. As for speeds, sea breeze strength reaches nearly 15 kmph (8 knots) from March to July and is nearly 12-13 kmph (7 knots) during the remaining months.

The above analysis makes it evident that despite strong surface westerlies, the SE/S sea breeze at Madras is pervasive with sustained and relatively strong wind speeds for a prolonged time span. The predominance of SE/S as the most favourable directions and the absence of any northerly component in the sea breeze at Chennai could be readily explained. The sea breeze at Chennai is the resultant vector of southwesterly shore wind and the easterly wind of the solenoidal circulation, which is so owing to the north-south orientation of the seacoast at Chennai. This gives rise to a SE sea breeze. However the role of Coriolis force in the maintenance of the southerly component (Asnani,1993) cannot be ignored. The blowing of near southerly sea breeze also explains the occasional occurrence of sea breeze setting in first at Chennai AP and then at Chennai city located closer to the coast but north of Chennai AP (Fig.1). Examination of the numerous anemograms revealed that, once SBO has taken place, establishment of steady state sea breeze flow resulting from the balancing of solenoidal flow with the frictional drag of the land is remarkably quick.

5.10. *Anti sea breeze*

Sea breeze is a solenoidal closed circulation. Thus there must be a compensating shore flow above the sea breeze front. Mukherjee *et al*. (1985) have called this flow as 'anti sea breeze'. At Chennai the normal wind during June-September in all the lower levels are strong monsoon westerlies. The extent of easterly sea breeze could be easily detected but determination of westerly anti sea breeze above the sea breeze front, when the prevalent flow itself is westerly appears intractable and imponderable. It has to be conceded that the normal wind pattern itself aids the development of anti sea breeze and in making the sea breeze circulation a closed one.

6. Summary

A brief summary of the study is provided here in below:

(*i*) The time of sea breeze onset over Chennai and Chennai AP and time of withdrawal for Chennai AP for the 8 month and 15 year period, 1 March - 31 October, 1969-83 have been objectively determined. Normal time of onset and withdrawal have been derived.

(*ii*) The normal onset time thus obtained varied between 1130-1525 hrs for Chennai and 1230-1610 hrs for Chennai AP. The normal onset time at Chennai AP was 40 - 70 minutes later than that of Chennai. The standard deviation varied between 40-125 minutes.The intra-annual variation of time onset could be adequately explained by the variation of maximum temperature and also by invoking the concept of mixing depth.

(*iii*) Utilising the concept of superposed epoch analysis normal profiles of temperature and relative humidity with reference to the onset time were derived for the 8-month period. This has shown that the occurrence of sea breeze at Chennai substantially controls the diurnal variation of surface temperature.

(*iv*) At Chennai AP the normal time of sea breeze withdrawal varied between 0000 to 0245 hrs and the duration of the sea breeze between 8 and 14 hours.

(*v*) The normal depth of sea breeze was generally under 1 km. The maximum sea breeze speed with reference to the height was reached just above the ground.

(*vi*) The sea breeze at Chennai generally blew from southeasterly or southerly direction and rarely from easterly direction and generally did not have a northerly component.

(*vii*) The sea breeze attained a normal sustained intensity of 10- 20 kmph.

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